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Neutron Spectroscopy for pulsed beams with frame overlap using a double time-of-flight technique

K.P. Harrig [a,*], B.L. Goldblum [a], J.A. Brown [a], D.L. Bleuel [b], L.A. Bernstein [a,c], J. Bevins [a], M. Harasty [a], T.A. Laplace [a], E.F. Matthews [a]

[a] *Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA*
[b] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[c] *Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*

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ABSTRACT

A new double time-of-flight (dTOF) neutron spectroscopy technique has been developed for pulsed broad spectrum sources with a duty cycle that results in frame overlap, where fast neutrons from a given pulse overtake slower neutrons from previous pulses. Using a tunable beam at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory, neutrons were produced via thick-target breakup of 16 MeV deuterons on a beryllium target in the cyclotron vault. The breakup spectral shape was deduced from a dTOF measurement using an array of EJ-309 organic liquid scintillators. Simulation of the neutron detection efficiency of the scintillator array was performed using both GEANT4 and MCNP6. The efficiency-corrected spectral shape was normalized using a foil activation technique to obtain the energy-dependent flux of the neutron beam at zero degrees with respect to the incoming deuteron beam. The dTOF neutron spectrum was compared to spectra obtained using HEPROW and GRAVEL pulse height spectrum unfolding techniques. While the unfolding and dTOF results exhibit some discrepancies in shape, the integrated flux values agree within two standard deviations. This method obviates neutron time-of-flight spectroscopy challenges posed by pulsed beams with frame overlap and opens new opportunities for pulsed white neutron source facilities.

1. Introduction

Fast neutron spectroscopy has been performed using a wide range of techniques, including time-of-flight (TOF) approaches [1–3], proton recoil spectrometry [4–6], and pulse height and activation foil unfolding methods [7–10]. This work focuses on enabling neutron TOF spectroscopy, where the time of travel of the neutron is measured over a fixed distance, in previously inaccessible regimes. For broad spectrum pulsed neutron sources, frame overlap can result in ambiguous TOF signals where fast neutrons from a given pulse have the same observable TOF as slower neutrons from previous pulses. As a result, neutron TOF experiments with pulsed sources have traditionally been limited by the duty cycle of the source [11,12].

Approaches to enabling TOF spectroscopy in pulsed beam scenarios have largely focused on physically filtering the neutron energy range, including the use of mechanical beam choppers [13] and electrostatic deflectors [14]. In addition to these filters, many pulsed source TOF measurements are forced to implement low-energy software thresholds to eliminate "wrap-around" effects, which can greatly limit low-energy spectral data [15]. Some approaches use shorter flight paths to detect the full energy range, thereby increasing the overall uncertainty of the TOF measurement and decreasing the energy resolution [16].

Building on the work of Schweimer [17], a new method for neutron TOF spectroscopy tailored for pulsed sources with frame overlap has been developed. Neutron–proton elastic scattering kinematics is exploited using a double TOF (dTOF) technique that allows for pulse association of temporally ambiguous neutron TOF signals. This technique is demonstrated using a pulsed deuteron breakup neutron source at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL). Descriptions of the facility, experimental setup, electronics, and materials are provided in Section 2. Section 3 details the dTOF approach, efficiency simulations of the scintillator array, and foil activation analysis methods. The measured neutron energy spectrum is provided in Section 4 and compared to results obtained using pulse height spectrum unfolding methods. Concluding remarks are presented in Section 5.

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[*] Corresponding author.
E-mail address: kharrig@berkeley.edu (K.P. Harrig).

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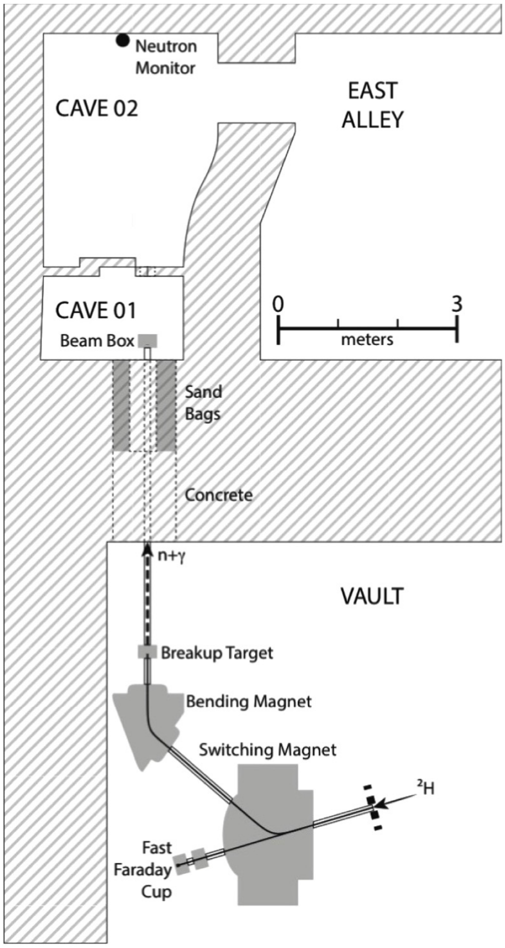

Fig. 1. Schematic representation of the 88-Inch Cyclotron vault and beam line to Cave 0. The Cave 0 experimental endstation is comprised of two enclosures, Cave 01 and Cave 02, separated by a lead-lined door outfitted with a beam port.

2. Experimental setup

The 88-Inch Cyclotron at LBNL is a variable energy, high-current, multi-particle cyclotron capable of accelerating deuterons up to a maximum energy of 65 MeV with maximum currents on the order of 10 particle-μA. In this work, a ^{2}H$^+$ beam was accelerated to 16 MeV at a current of ∼180 nA during the neutron scattering measurements, ∼0.66 nA during the neutron singles pulse height measurements, and ∼1.8 μA during the foil irradiation. The deuteron beam was directed along the Cave 0 beam line and optically aligned using a phosphor located in the Cave 01 beam box, as shown in Fig. 1. A Faraday cup located inside the cyclotron vault was equipped with a 3-mm-thick beryllium breakup target with a tantalum backing and plunged along the Cave 0 beam line [3,18]. The beryllium target is embedded in a 3.8-mm-thick electrically isolated tantalum disk and backed by a 14.5-mm-thick copper cooling assembly. The resulting neutrons and photons entering the experimental area were collimated by ∼3 m of concrete and ∼1.5 m of sand bags encasing the beam pipe, producing an open-air neutron beam in the experimental area.

As the 88-Inch Cyclotron is a pulsed ion source, the 16 MeV ^{2}H$^+$ beam corresponds to a cyclotron radio frequency of 6.31 MHz and a pulse period of 158.5 ns. The standard deviation of the temporal profile of the incoming beam pulse was approximately 6 ns. For the 16 MeV beam with a flight path of 6.84 m, for instance, neutrons with energies less than 9.87 MeV (i.e., TOF $>$ 158.5 ns) overlap with neutrons and gamma rays from the subsequent beam pulse.

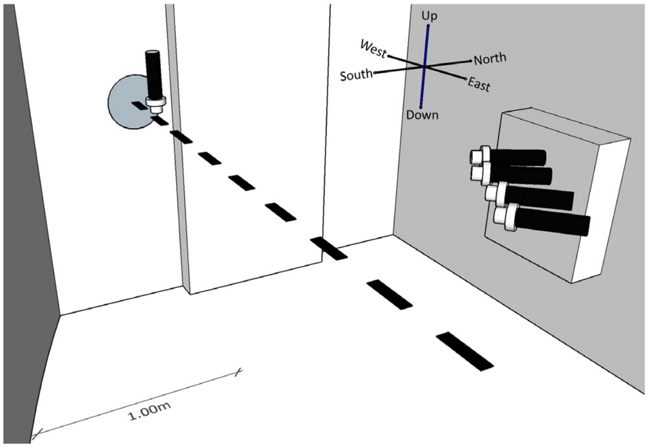

Fig. 2. Schematic view of the scintillator array in the Cave 02 experimental area. The black dashed line indicates beam line center.

Table 1
Target and scatter cell configuration. The x-coordinate was determined relative to the west wall, the y-coordinate relative to beam line center, and the z-coordinate relative to the plane of the beam. Each coordinate was measured using a cross-line laser level. The flight path, L, is defined as the distance from the breakup target to the center of the target cell and the distance from the center of the target cell to the center of the scatter cells for the target and scatter cells, respectively. The angle, ϕ, was determined relative to the axis defined by the incoming beam.

Detector	x (cm)	y (cm)	z (cm)	L (cm)	ϕ (degrees)
Target	36.3	0	3.5	683.8	–
Scatter 0	154.1	99.5	0	154.2	40.2
Scatter 1	169.3	86.2	0	158.5	33.0
Scatter 2	187.7	76.6	0	169.7	26.9
Scatter 3	204.5	65.0	0	180.3	21.1

The dTOF measurements were performed using an array of pulse-shape-discriminating organic liquid scintillators. The scintillator array was composed of one cell in beam (i.e., target cell) and four cells out of beam (i.e., scatter cells), illustrated in Fig. 2. The cells consisted of cylindrical Hamamatsu H1949–50 photomultiplier tubes (PMTs) biased from −1.75 to −2.1 kV, coupled to cylindrical liquid organic EJ-309 scintillators, and were positioned using adjustable camera tripods. All scintillators had a height of 5.08 cm, a diameter of 5.08 cm, and were enclosed by an aluminum casing.

The flat aluminum surface of the target cell, with the scintillator oriented in the outward direction (away from the PMT face) was aligned vertically and configured in beam line center. The flat face of the aluminum surface was mounted 3.5 cm above the plane of the beam line and the center of the flat surface was placed 36.3 cm from the west wall of Cave 02, where the beam entered the experimental space. The scatter cells were configured in the plane of the beam line and oriented such that the outward normal of the flat aluminum surfaces faced the target cell. Each of the scatter cells were placed at varying flight paths and angles relative to the center of the target cell, as described in Table 1.

A block diagram of the signal chain for data acquisition is shown in Fig. 3. The timing of the PMT output signals was established using constant fraction discrimination (CFD) via two mesytec MPD-4 modules, one to process the four scatter cell signals and one for the target cell signal. The CFD output signals for each cell were fed into a CAEN V1290N multi-hit time-to-digital converter (TDC) operating in trigger matching mode with the clock multiplier of the module set to 195 ps resolution. The pulse height (Amp.) and pulse shape (TAC) data for each input signal were obtained using the MPD-4 modules as fast variable gain input amplifiers whose signal was fed to a CAEN V785 peak sensing analog-to-digital converter (ADC).